

# *Heavy quarkonium in hot medium*



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# *Heavy quarkonium in hot medium*

*-- conceptions and misconceptions --*



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Matsui & Satz, PLB178 (1986) 416

“ $J/\psi$  Suppression by Quark-Gluon Plasma Formation”

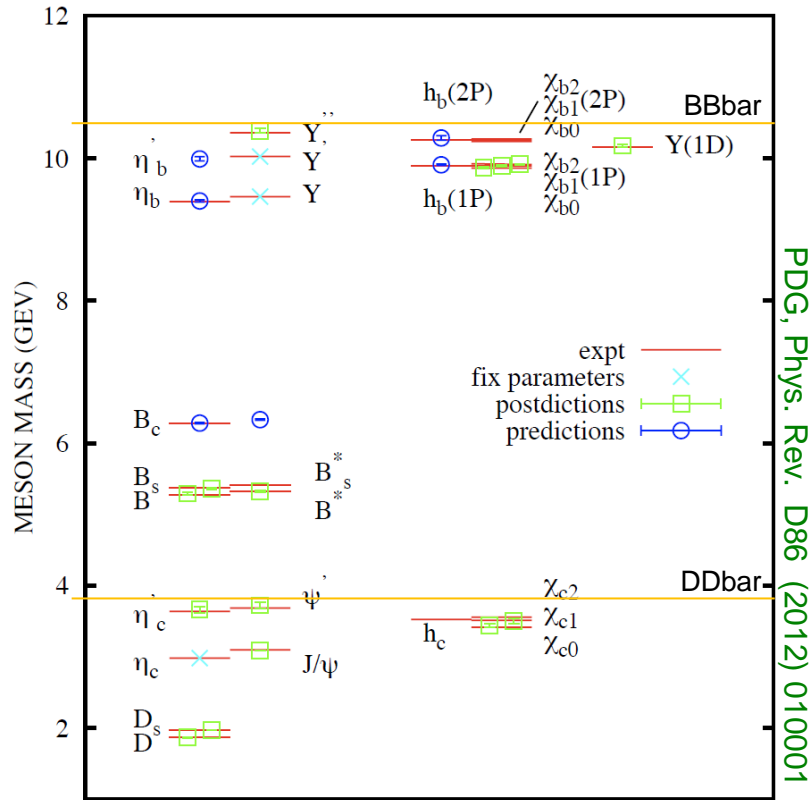
Hashimoto, Hirose, Kanki & Miyamura, PRL 57 (1986) 2123

“Mass Shift of Charmonium near Deconfinement Temperature and Possible Detection in Lepton Pair Production”

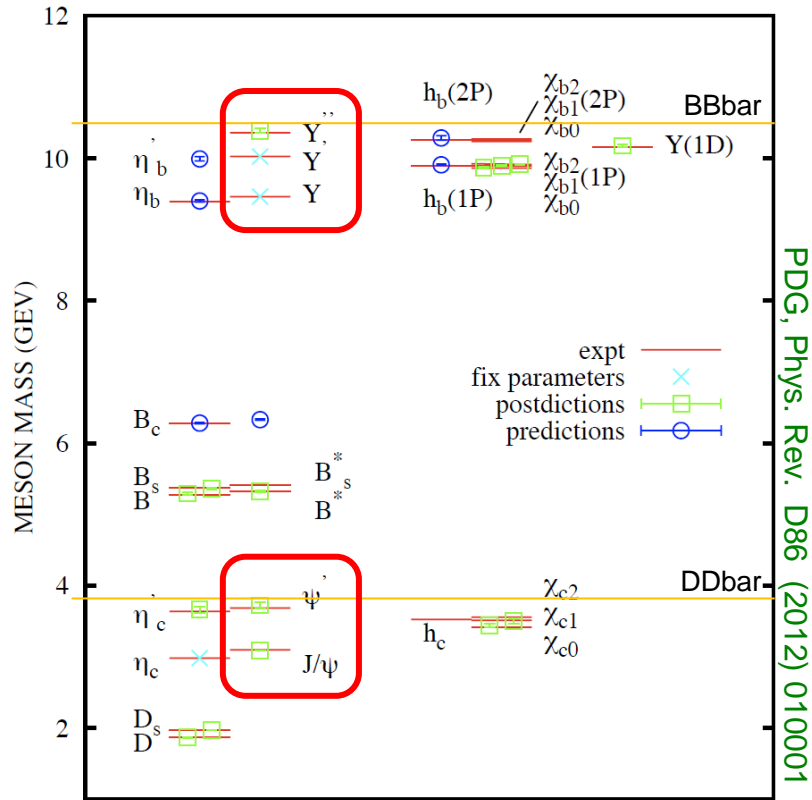
### *Outline of this talk*

1. Heavy QQbar : brief introduction
2. “Free Energy” at  $T \neq 0$
3. “Spectral Function” at  $T \neq 0$
4. “Thermal Decoherence” & “Complex Potential” at  $T \neq 0$
5. Summary

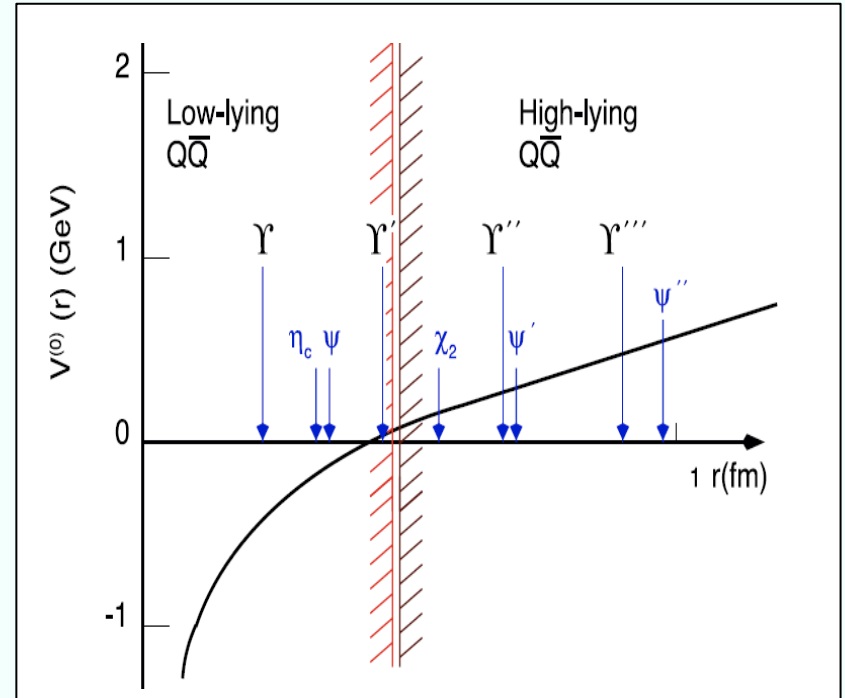
## Expt. vs. Lattice QCD at T=0

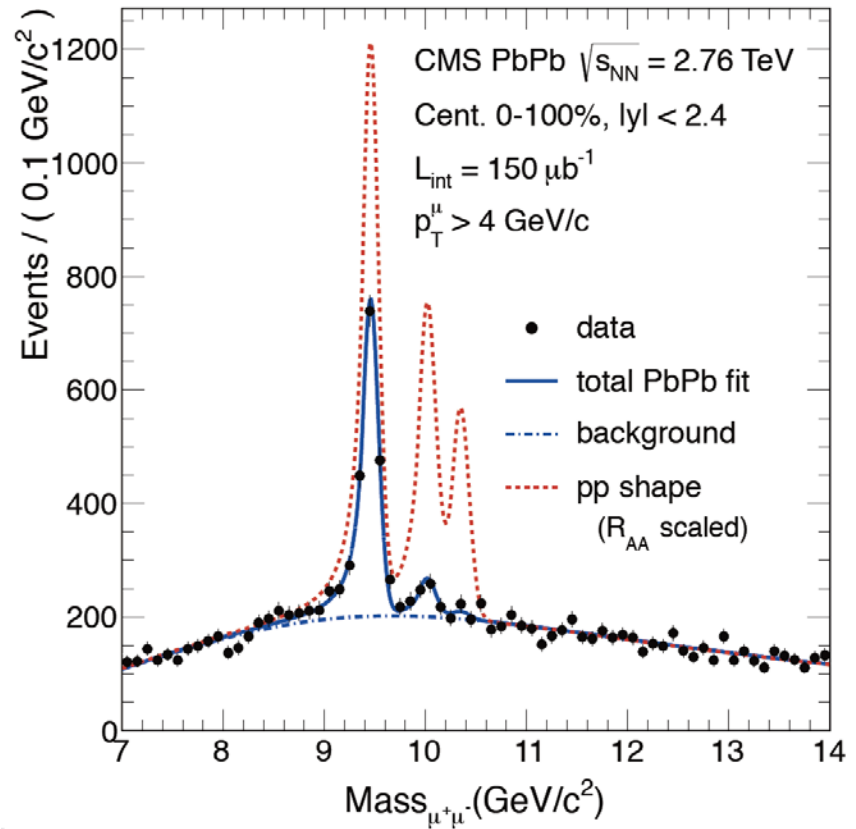
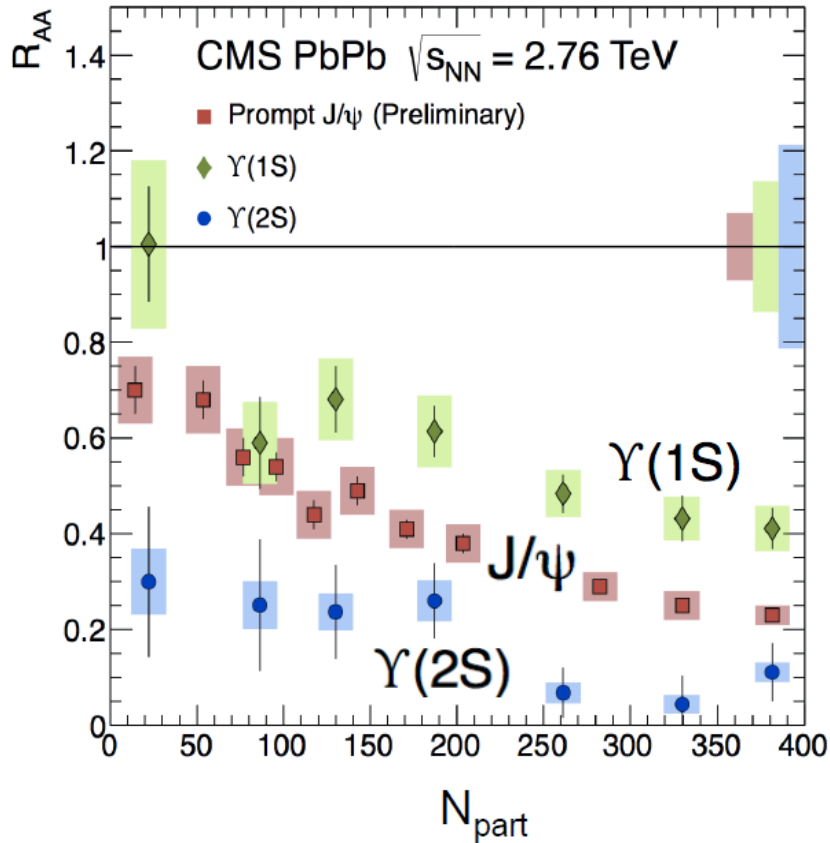


## Expt. vs. Lattice QCD at T=0



## Spatial size of QQbars



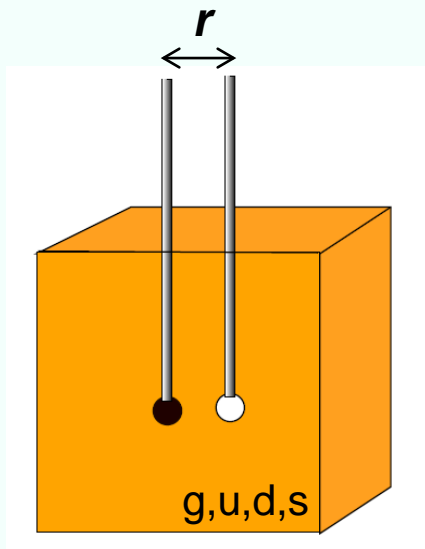


Roland [CMS Coll.], talk on Monday @QM2012  
 Rangal [CMS Coll.], talk on Tuesday @QM2012

What's new ?

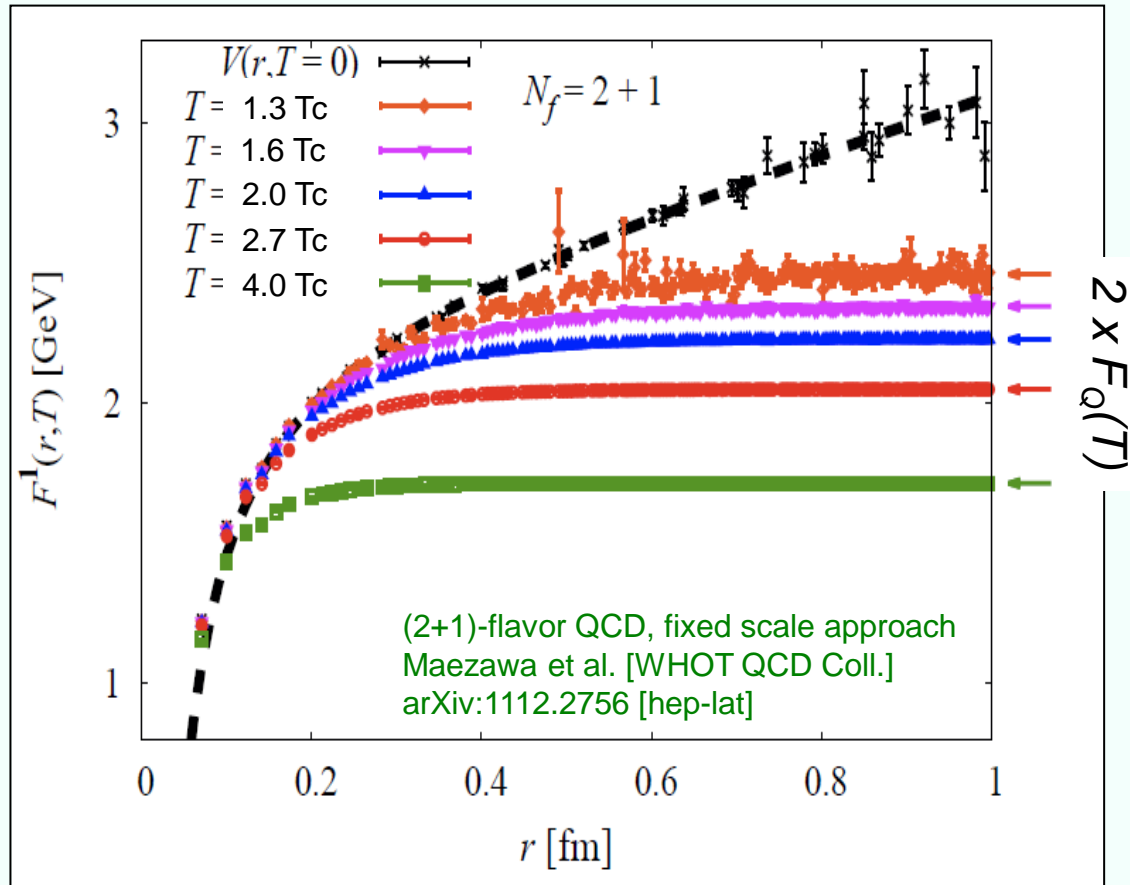
Expt.: Y(1S,2S,3S) in HIC

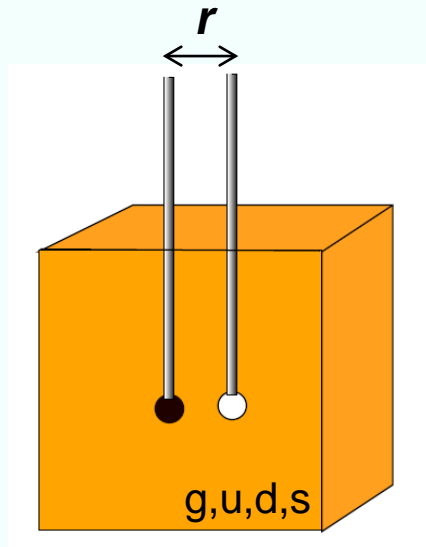
Theory: complex QQbar potential



Color-Singlet Free Energy  
(in Coulomb gauge)

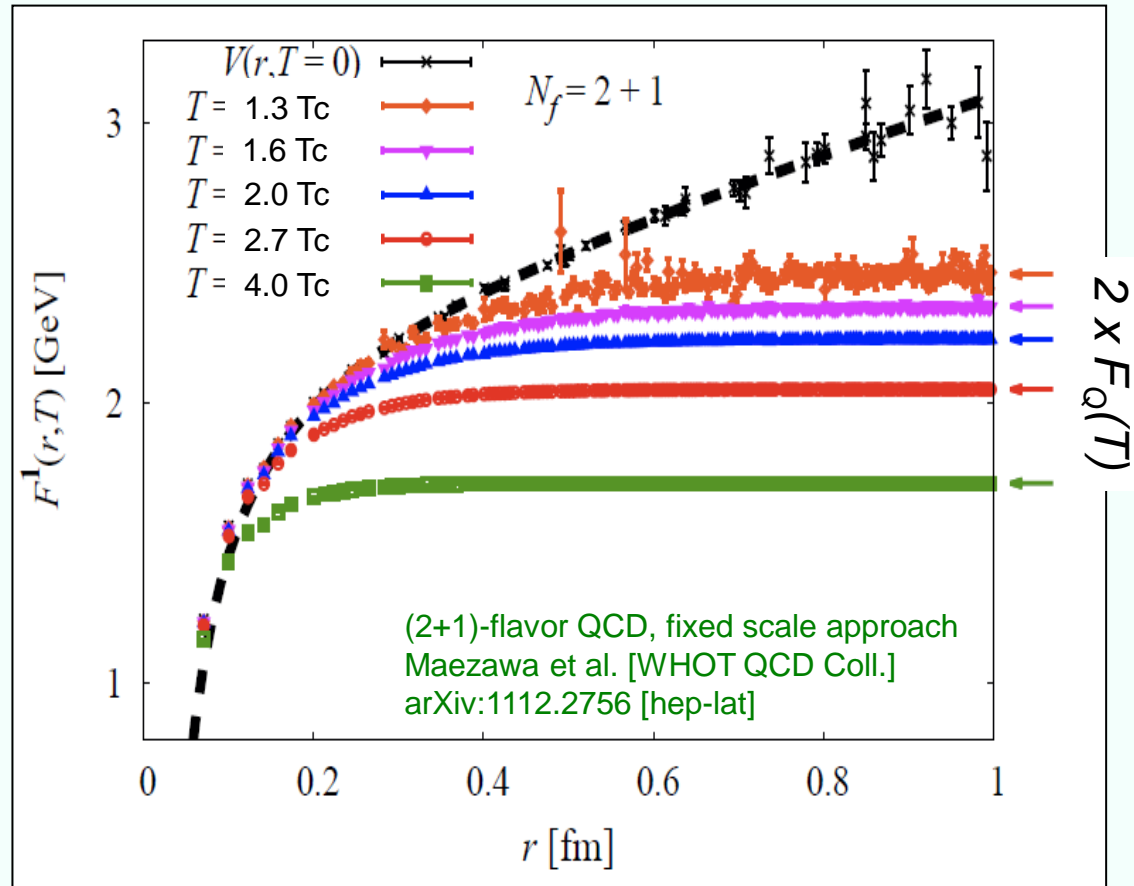
$$F^1(r, T) = -T \ln \langle \text{Tr} \Omega^\dagger(\mathbf{x}) \Omega(\mathbf{y}) \rangle$$





Color-Singlet Free Energy  
(in Coulomb gauge)

$$F^1(r, T) = -T \ln \langle \text{Tr} \Omega^\dagger(\mathbf{x}) \Omega(\mathbf{y}) \rangle$$

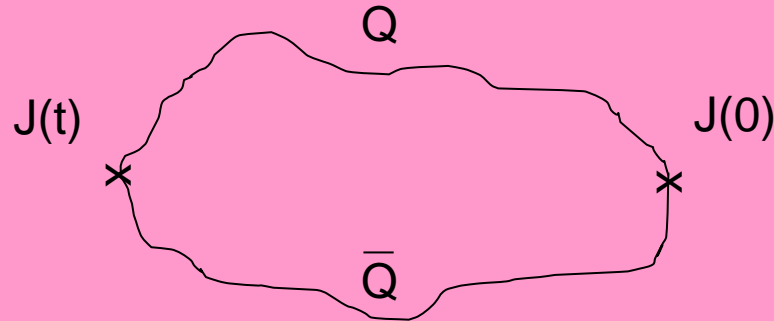


## Lessons from Free energy

- ✓  $F^1(r)$  : Nice screening and cluster properties
- ✓  $F^1(r)$  ,  $F^{\text{av}}(r)$  ,  $U(r)$  : NOT the in-medium QQbar potentials

Lattice QCD + Maximum Entropy Method (MEM)  $\Rightarrow$  spectral function (SPF)

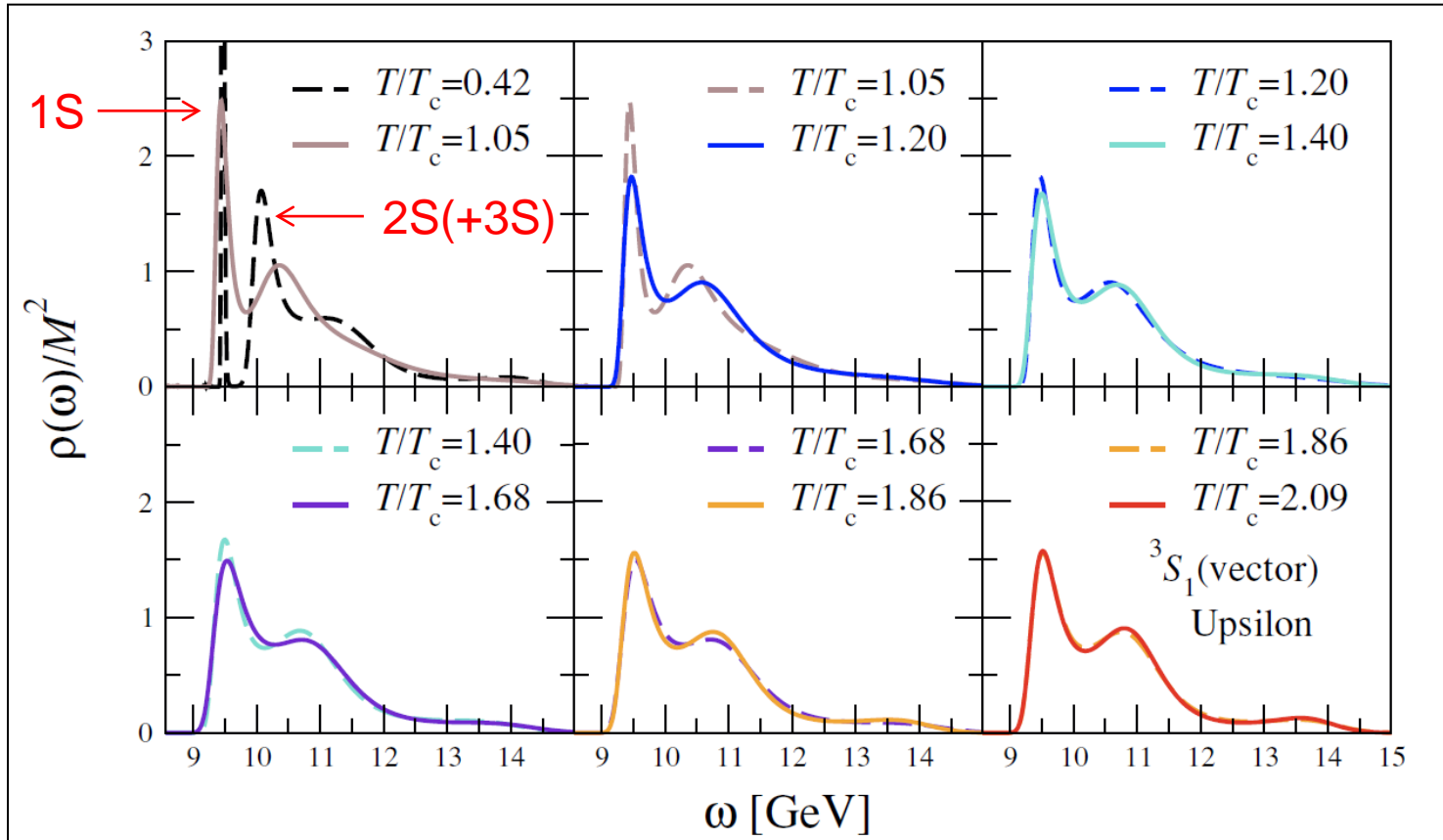
- Asakawa, Hatsuda & Nakahara, Prog. Part. Nucl. Phys. 46 (2001) 459.
- Asakawa & Hatsuda, Phys.Rev.Lett.92 (2004) 012001
- Datta, Karsch, Petreczky & Wetzorke, Phys.Rev.D69 (2004) 094507.
- Umeda, Nomura & Matsufuru, Eur.Phys.J.C39S1 (2005) 9.



Medium = gluons + light quarks

Lattice QCD + Maximum Entropy Method (MEM)  $\Rightarrow$  spectral function (SPF)

## Bottomonium ( $\Upsilon$ ) in Lattice NRQCD



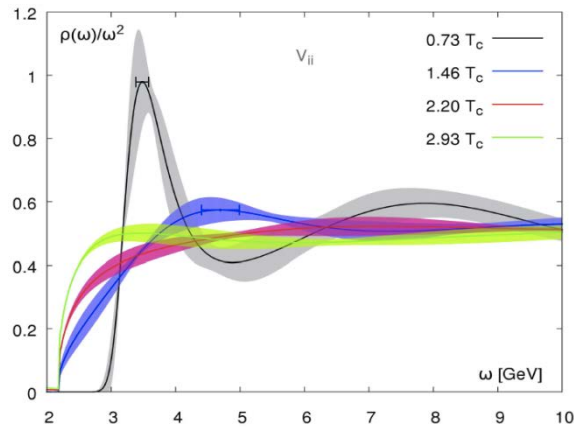
2-flavor NRQCD ( $M \gg T$ ):

Aarts, Allton, Kim, Lombardo, Oktay, Ryan, Sinclair, Skullerud, JHEP 11 (2011) 103

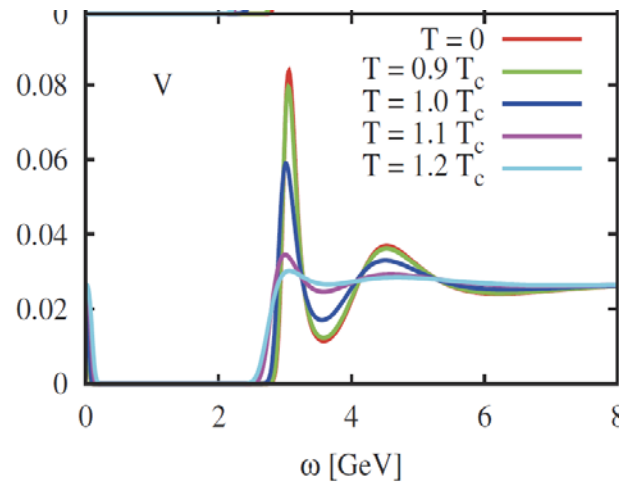
# Charmonium ( $J/\psi$ )

LQCD (quenched) : Ding, Francis, Kaczmarek, Karsch, Satz, Soeldner, arXiv:1204.4945; Ding (Parallel 2D)  
 QCDSR+MEM : Gubler, Morita, Oka, Phys. Rev. Lett. 107 (2011) 092003; Gubler (Poster 70)  
 QCDSR : Morita, Lee, Phys. Rev. C85 (2012) 044917  
 Holographic QCD : Grigoryan, Hohler, Stephanov, Phys. Rev. D82 (2010) 026005

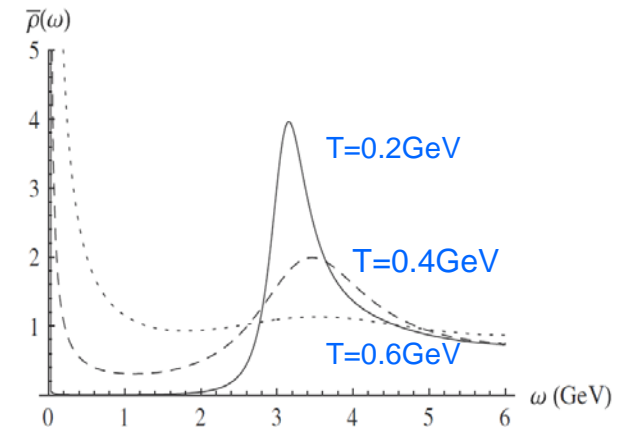
## Lattice QCD



## QCD sum rules



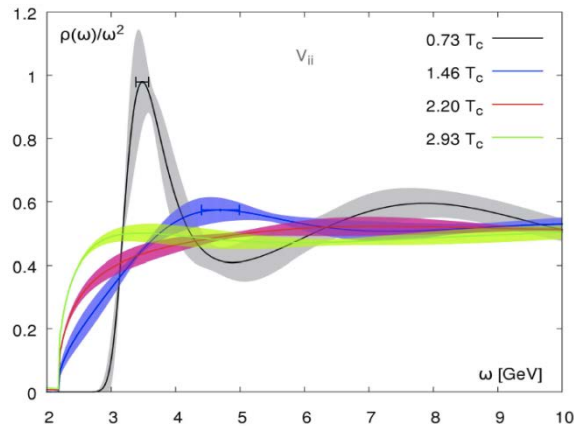
## Holographic QCD



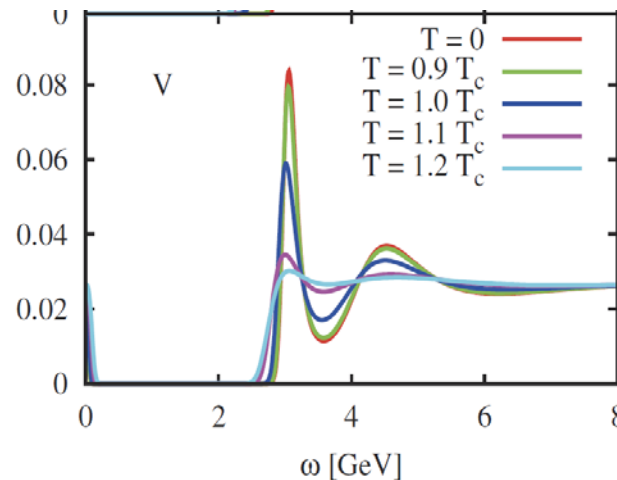
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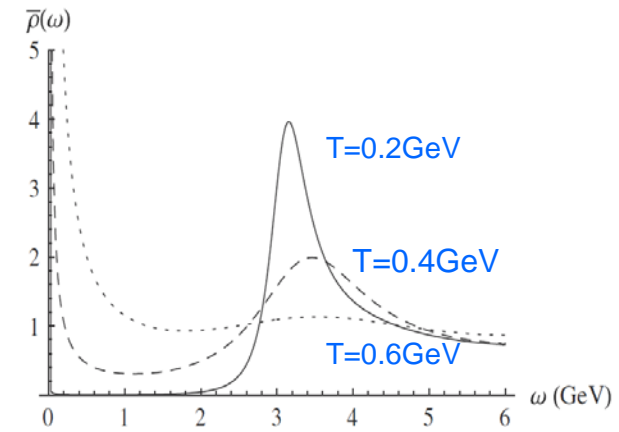
## Lattice QCD



## QCD sum rules



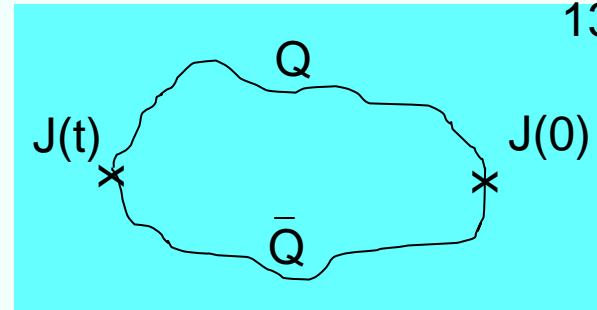
## Holographic QCD



## Lessons from Lattice Spectral Function

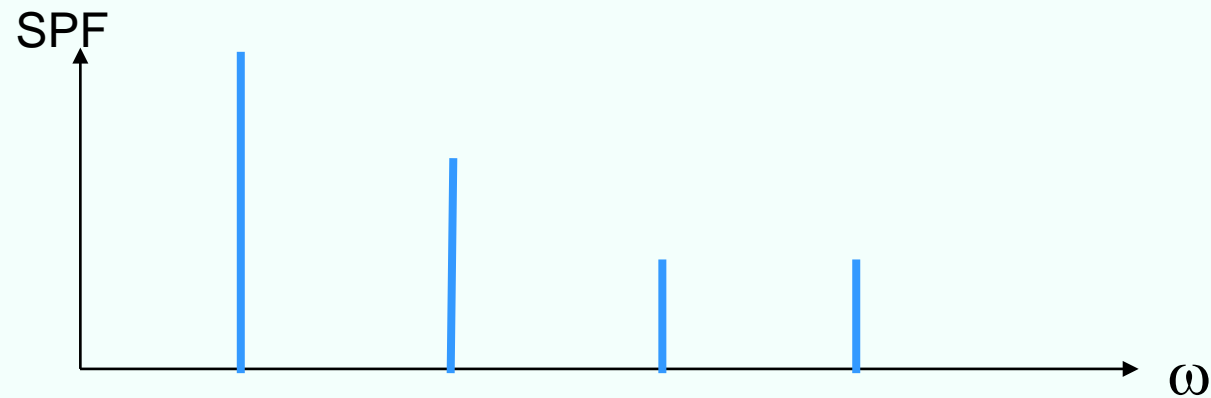
- ☑ Need improved MEM & better lattice data to identify nS states
- ☑ Need better understanding of the “width”

# Thermal “decoherence” at $T \neq 0$

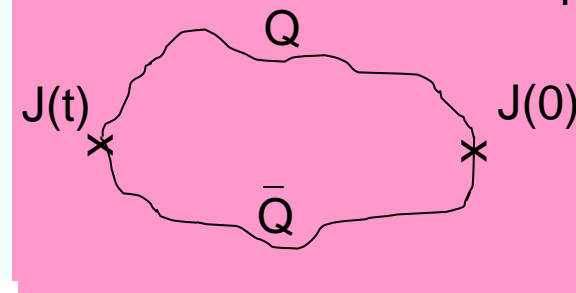


SPF at  $T=0$

$$\rho(\omega; T = 0) = \sum_m |\langle m | J | 0 \rangle|^2 \delta(\omega - E_m^{Q\bar{Q}})$$



# Thermal “decoherence” at $T \neq 0$

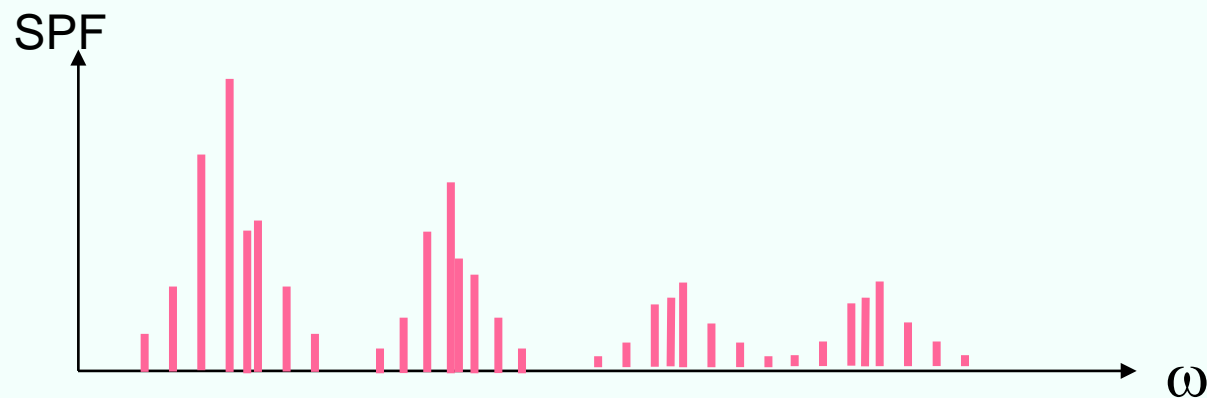


SPF at  $T=0$

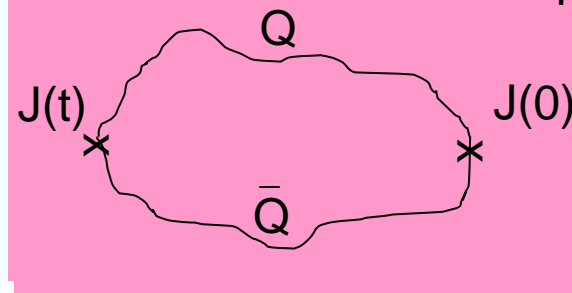
$$\rho(\omega; T = 0) = \sum_m |\langle m | J | 0 \rangle|^2 \delta(\omega - E_m^{Q\bar{Q}})$$

SPF at  $T \neq 0$

$$\rho(\omega; T \neq 0) = \sum_{m,n} e^{-E_n/T} |\langle m | J | n \rangle|^2 \delta(\omega - (E_m^{Q\bar{Q}} - E_n))$$



# Thermal “decoherence” at $T \neq 0$

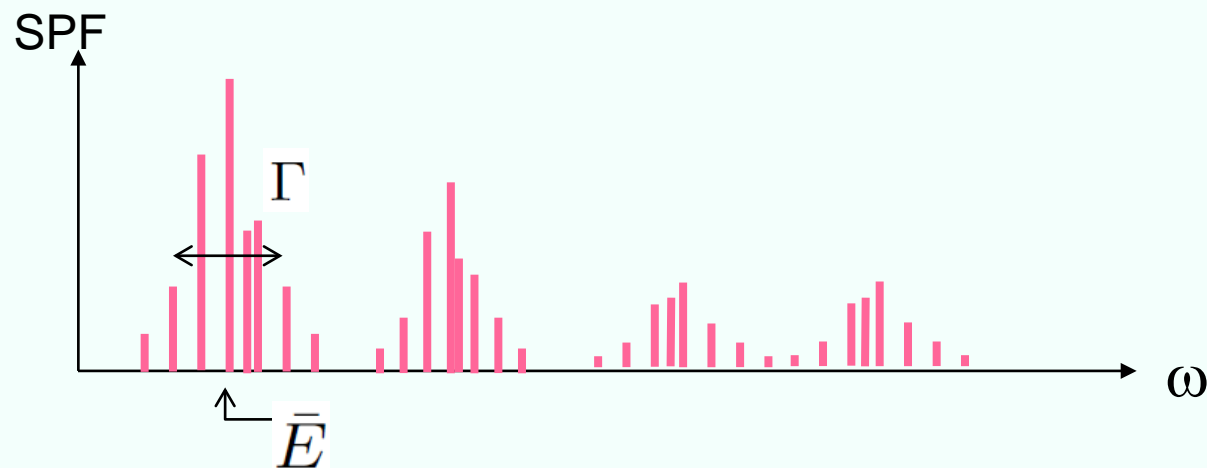


SPF at  $T=0$

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SPF at  $T \neq 0$

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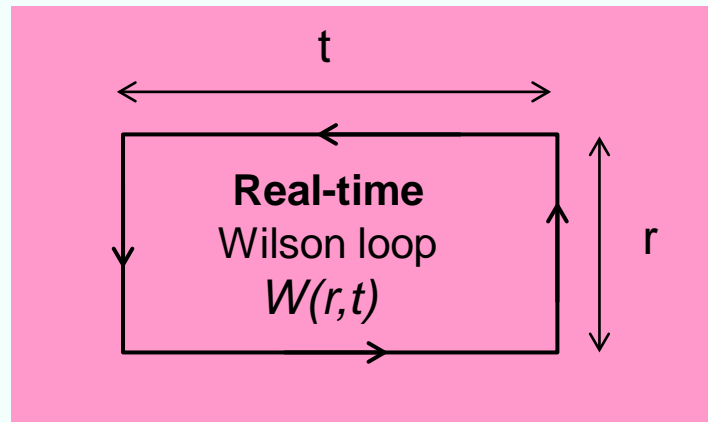


Thermal decoherence

$$\begin{aligned} \rho_{>}(t; T) = \langle J(t) J(0) \rangle &= \sum_{m,n} e^{-E_n/T} |\langle m | J | n \rangle|^2 e^{-i(E_m^{Q\bar{Q}} - E_n)t} \\ &\xrightarrow{t \rightarrow \infty} C e^{-i\bar{E}t - \Gamma t} \end{aligned}$$

# Non-Relativistic Effective Hamiltonian with Complex Potential

$$H_{\text{eff}} = \frac{-\nabla^2}{M_Q} + V_{\text{static}}(r, t) + \dots$$



$$V(r, t) = \frac{i\partial_t W(r, t)}{W(r, t)} = \text{Re}V(r, t) + i\text{Im}V(r, t)$$

Laine, Philipsen, Romatschke, Tassler, JHEP 03 (2007) 054.

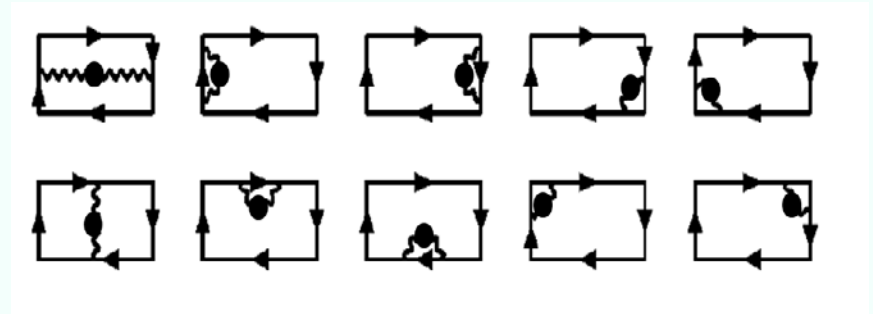
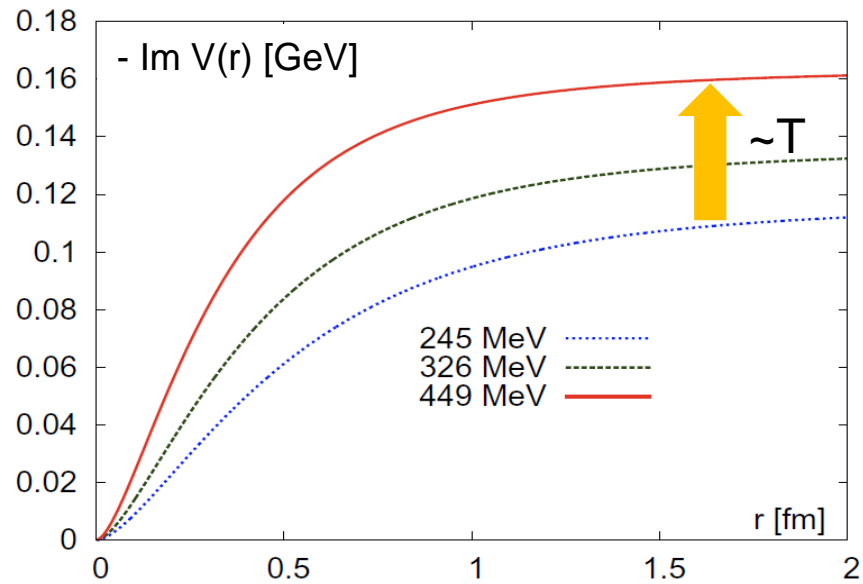
Burnier, Laine, Vepsalainen, JHEP 0801, 043 (2008)

See also: Brambilla, Ghiglieri, Vairo, Petreczky, Phys. Rev. D 78 (2008) 014017

Beraudo, Blaizot, Ratti, Nucl.Phys. A806 (2008) 312

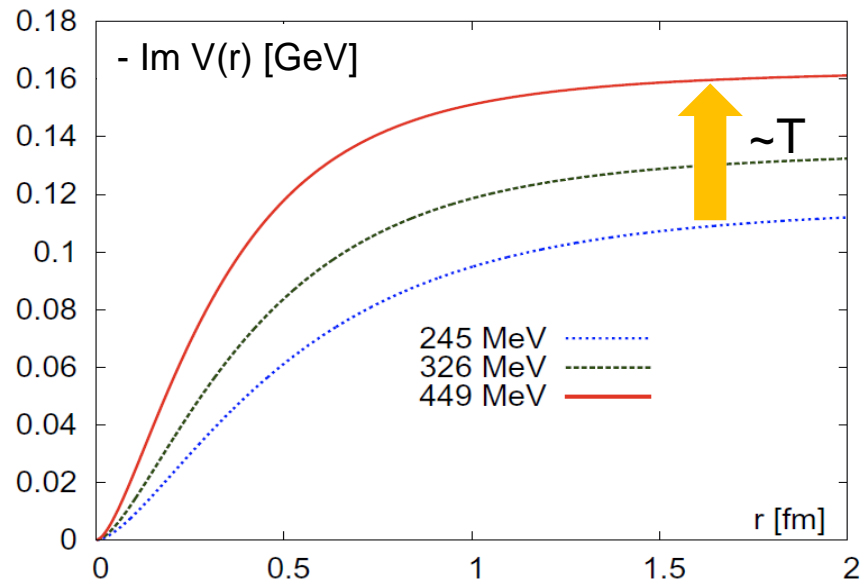
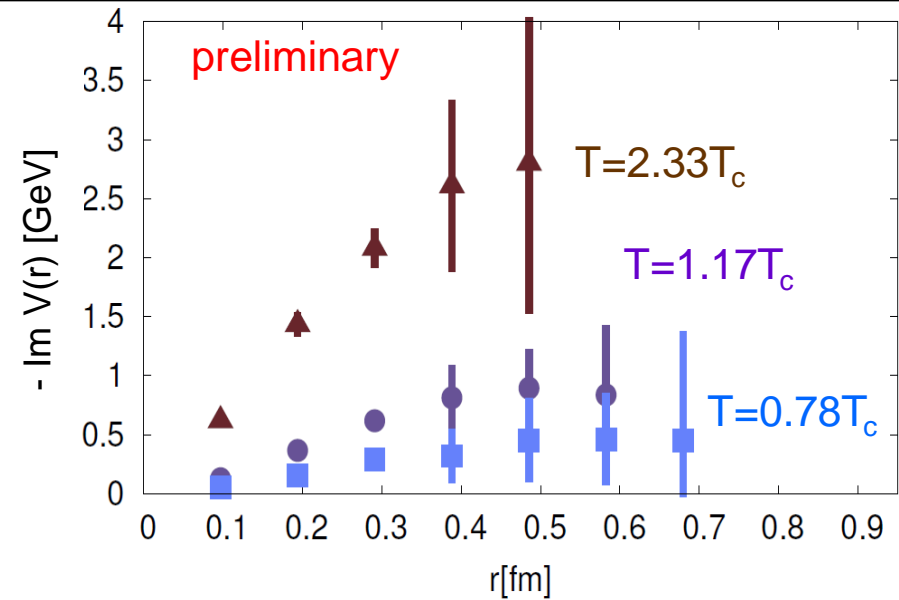
Rothkopf, Hatsuda, Sasaki, arXiv:0910.232 [hep-lat] .

pQCD ( $g^2 \ll 1, N_c=3$ )



Hard Thermal Loop resummation  
(in particular, Landau damping)

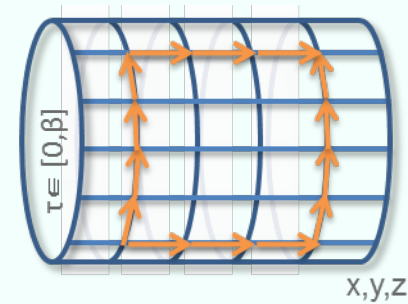
Laine et al., JHEP 03 (2007) 054.

pQCD ( $g^2 \ll 1, N_c=3$ )Lattice QCD ( $g^2 > 1, N_c=3$ )

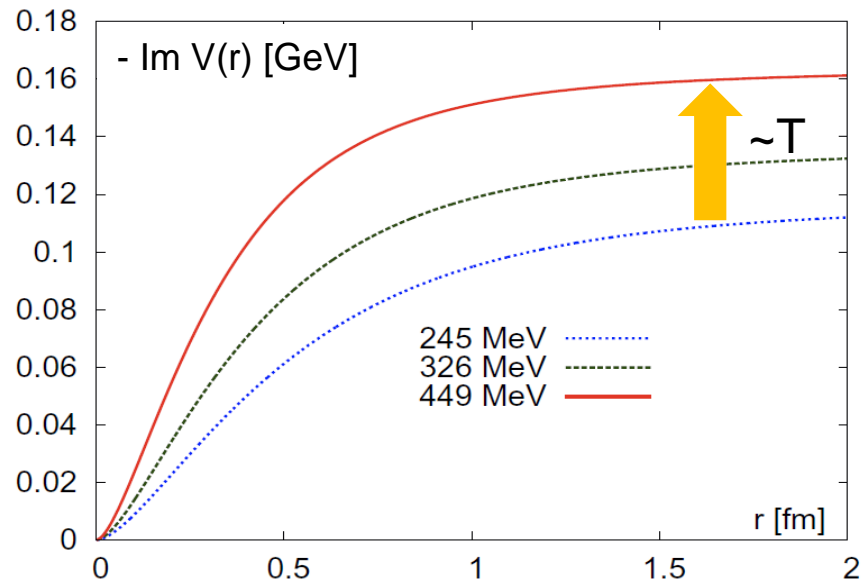
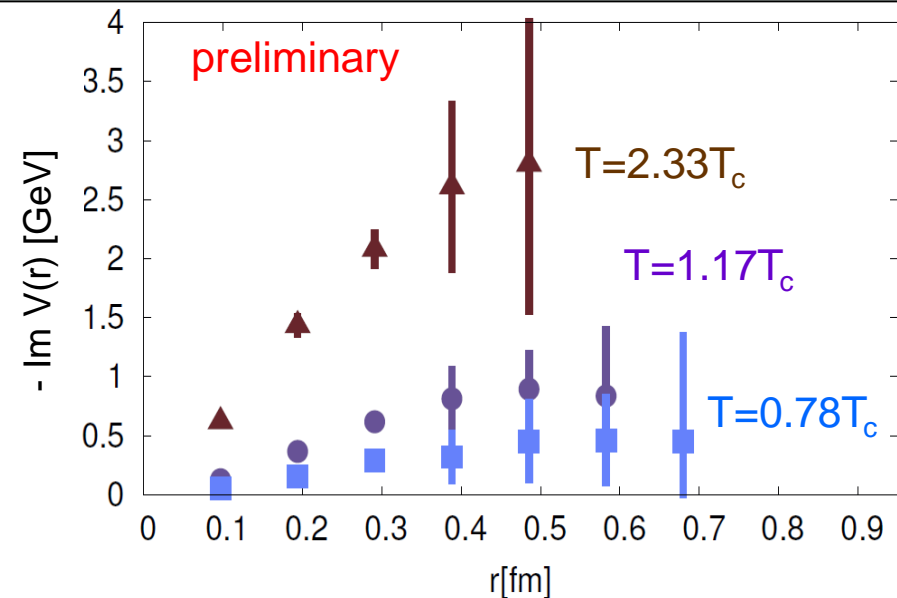
Laine et al., JHEP 03 (2007) 054.

Rothkopf, Hatsuda, Sasaki, PRL 108 (2012) 162001

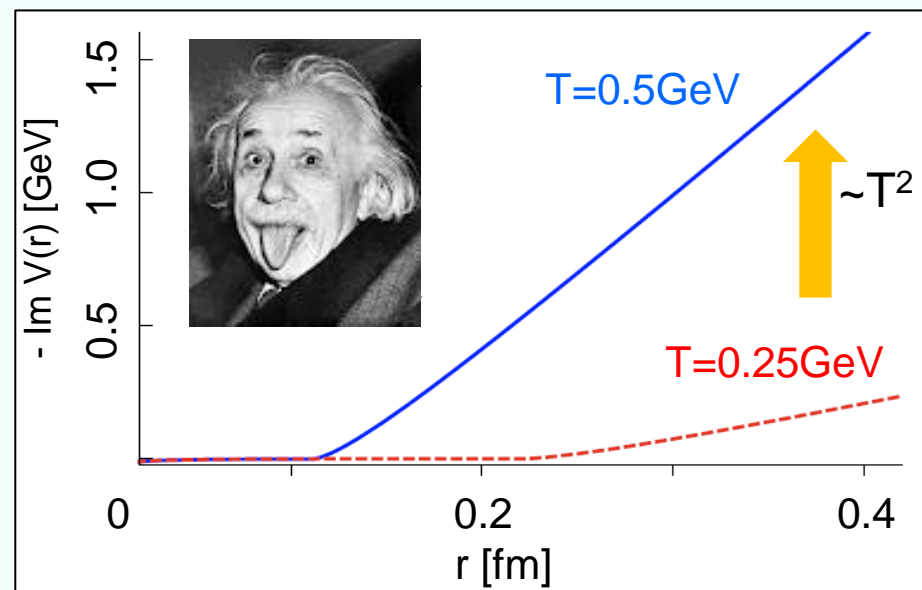
Burnier, Rothkopf, arXiv: 1208.1899

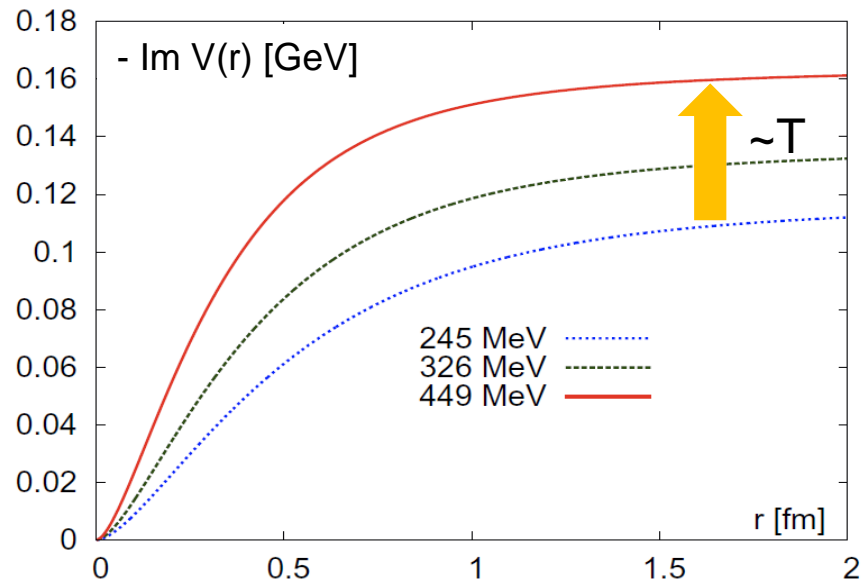
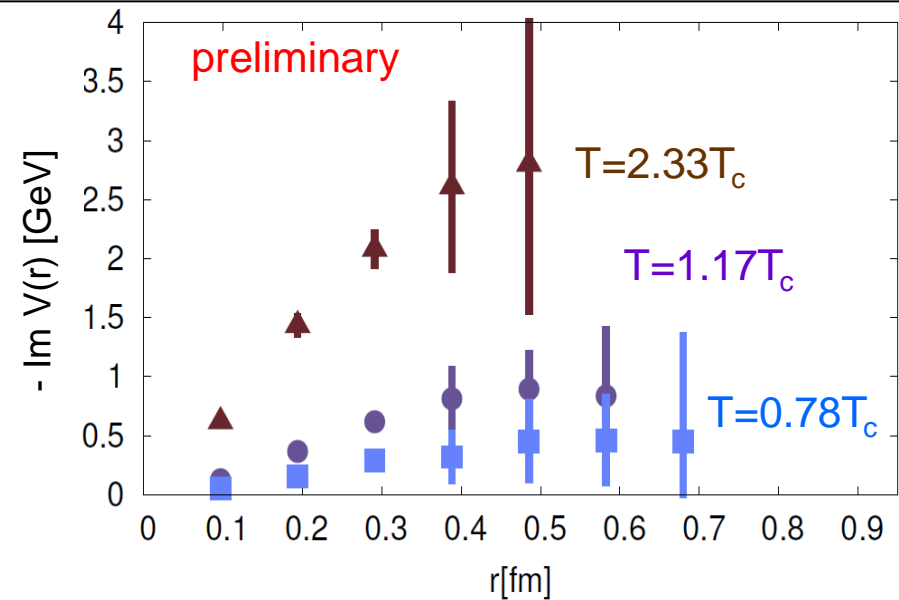


$$W(r, \tau) \rightarrow \rho(r, \omega) \rightarrow W(r, t)$$

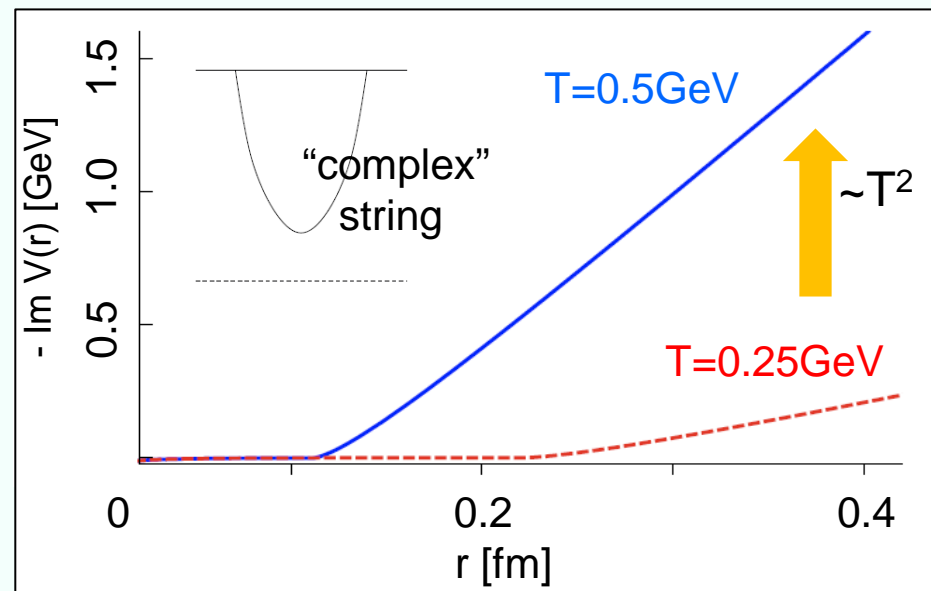
pQCD ( $g^2 \ll 1, N_c=3$ )Lattice QCD ( $g^2 > 1, N_c=3$ )

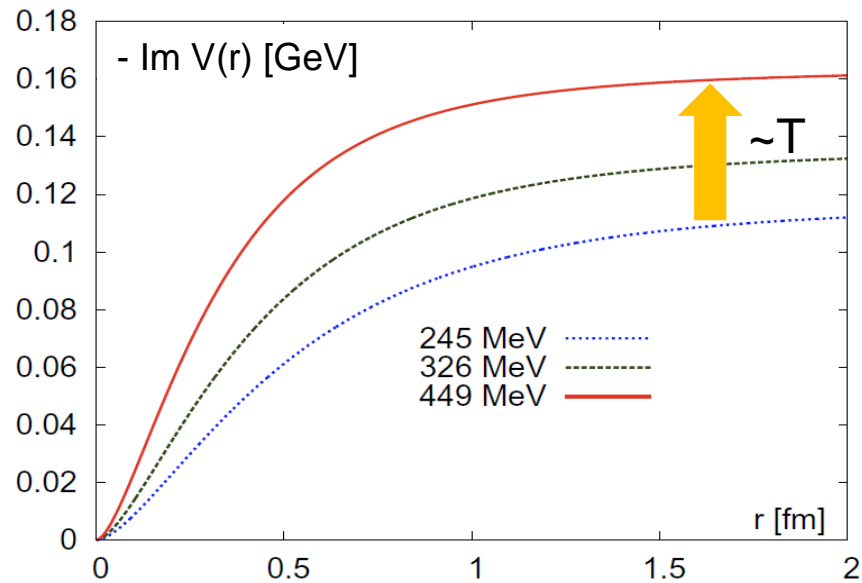
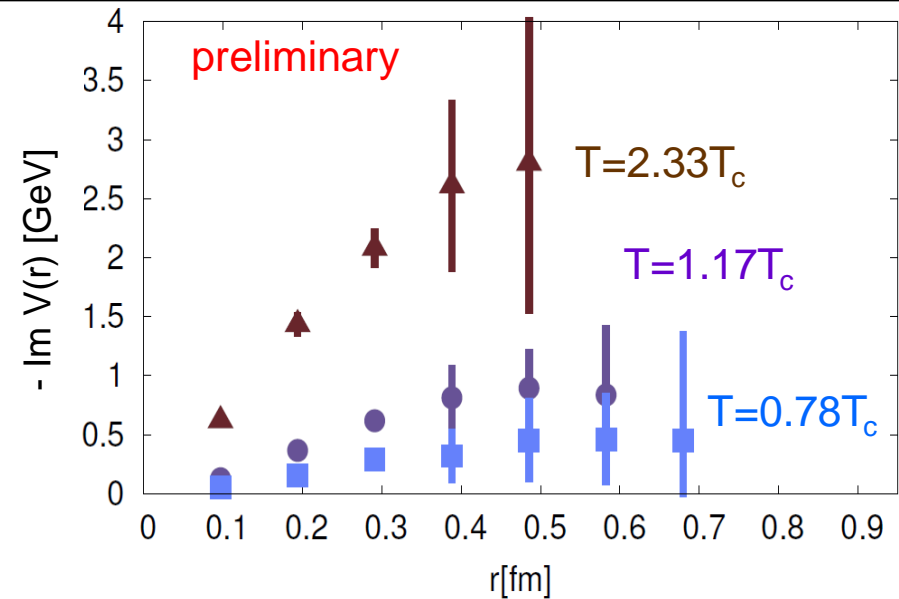
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Rothkopf, Hatsuda, Sasaki, PRL 108 (2012) 162001  
Burnier, Rothkopf, arXiv: 1208.1899Albacete, Kovchegov, Taliotis, PRD 78 (2008) 115007  
Grigoryan, Kovchegov, NPB 852 (2011) 1AdS/CFT ( $g^2 N_c \gg 1, N_c \gg 3$ )

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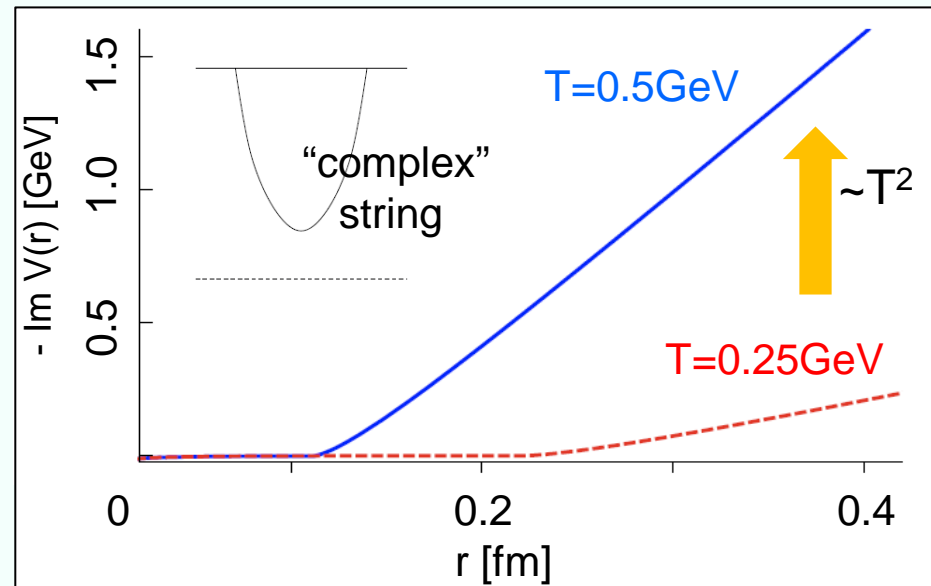
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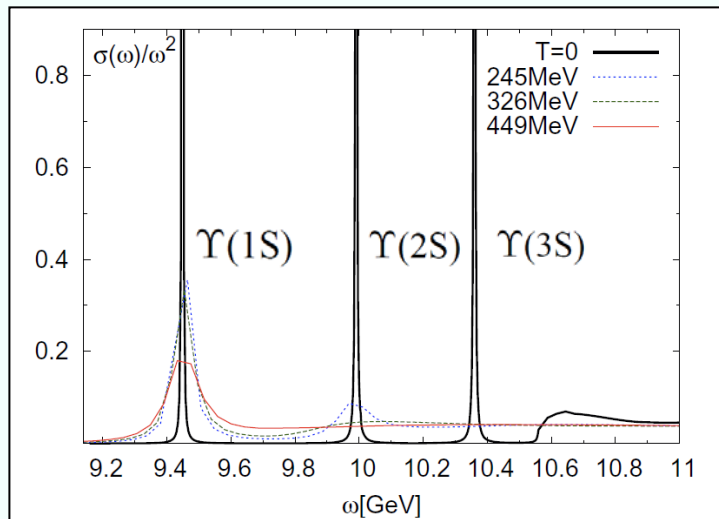
Rothkopf, Hatsuda, Sasaki, PRL 108 (2012) 162001  
Burnier, Rothkopf, arXiv: 1208.1899Albacete, Kovchegov, Taliotis, PRD 78 (2008) 115007  
Grigoryan, Kovchegov, NPB 852 (2011) 1Lessons from Im  $V(r)$ 

- similar behavior in diff. approaches
- Im  $V$  important at RHIC/LHC ?

AdS/CFT ( $g^2 N_c \gg 1, N_c \gg 3$ )

Petreczky, Miao, Mocsy, NPA 855 (2011) 125

Petreczky (Parallel 1D)



$$\left[ -\frac{1}{m} \vec{\nabla}^2 + V(r, T) - E \right] G^{nr}(\vec{r}, \vec{r}', E, T) = \delta^3(r - r')$$

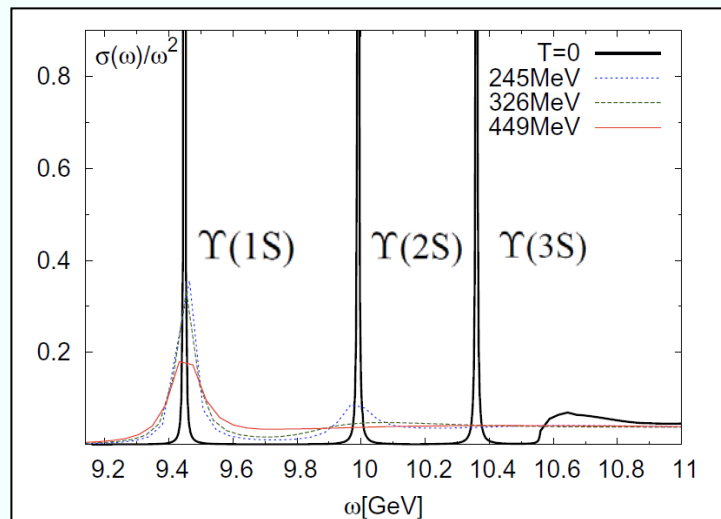
$$\sigma(\omega, T) = \frac{6}{\pi} \text{Im} G^{nr}(\vec{r}, \vec{r}', E)|_{\vec{r}=\vec{r}'=0} \quad E = \omega - 2m.$$

Strassler & Peskin, PRD 43 (1991) 1500

# Spectral function from complex $V$

Petreczky, Miao, Mocsy, NPA 855 (2011) 125

Petreczky, (Parallel 1D)

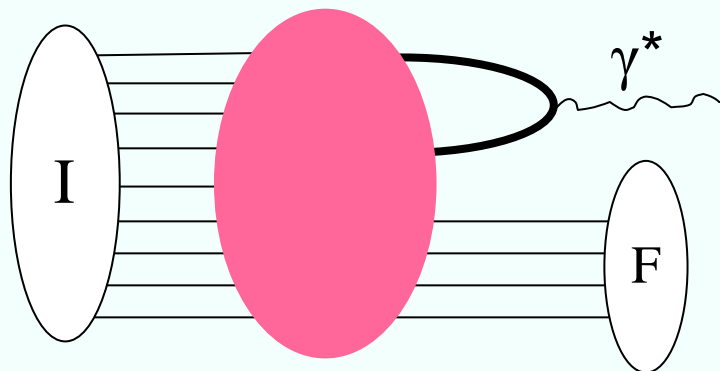


$$\left[ -\frac{1}{m} \vec{\nabla}^2 + V(r, T) - E \right] G^{nr}(\vec{r}, \vec{r}', E, T) = \delta^3(r - r')$$

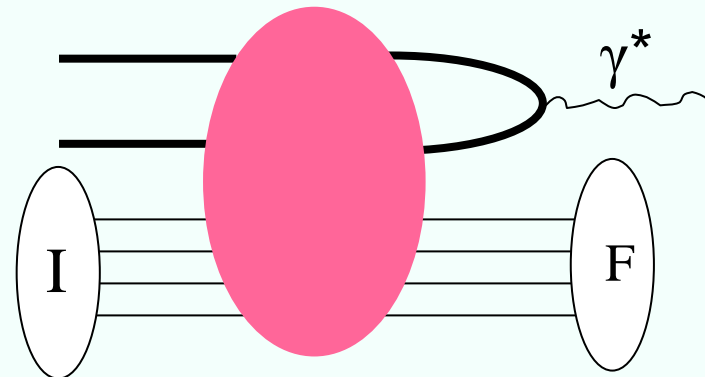
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Strassler & Peskin, PRD 43 (1991) 1500

**CAUTION !**

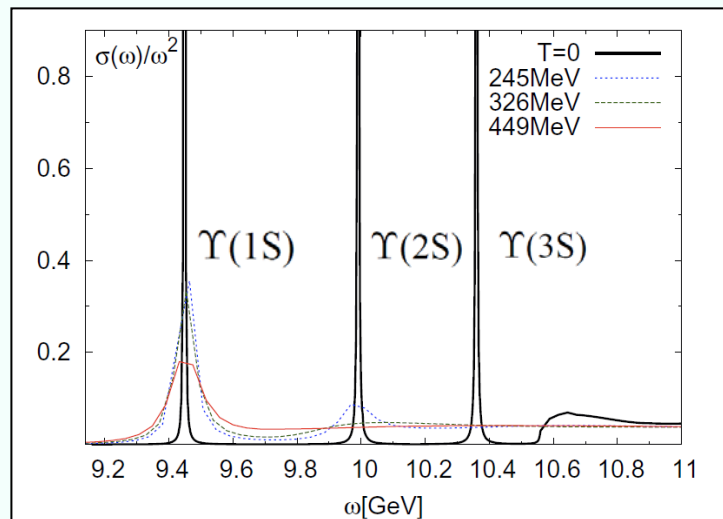


Is related to SPF through optical theorem

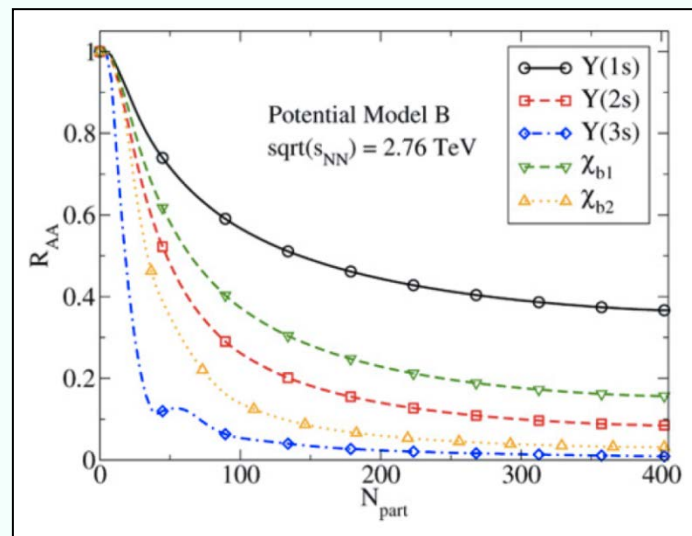


real situation for  $Y$  at RHIC/LHC

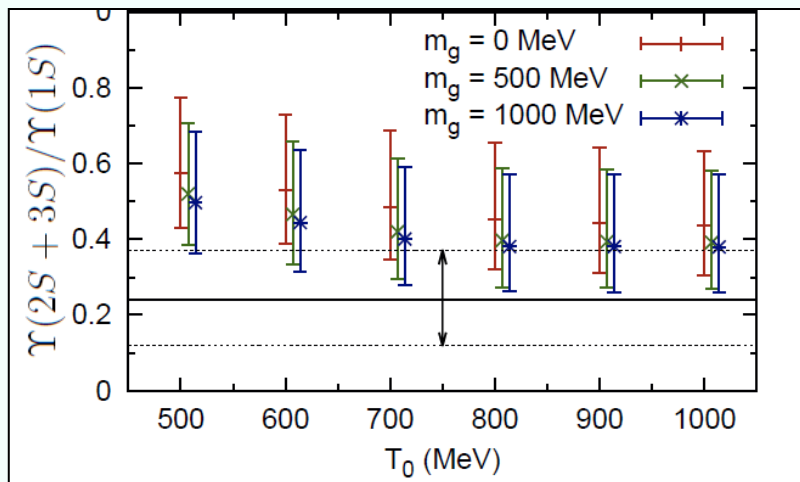
Petreczky, Miao, Mocsy, NPA 855 (2011) 125  
 Petreczky, (Parallel 1D)



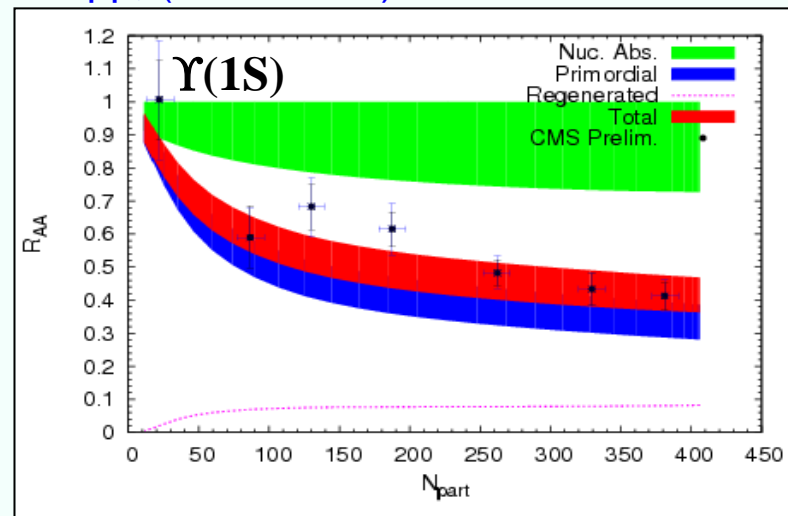
Strickland & Bazow, NPA 879 (2012) 25



Brezinski, Wolschin PL B707 (2012) 534  
 Wolschin (Poster 81)



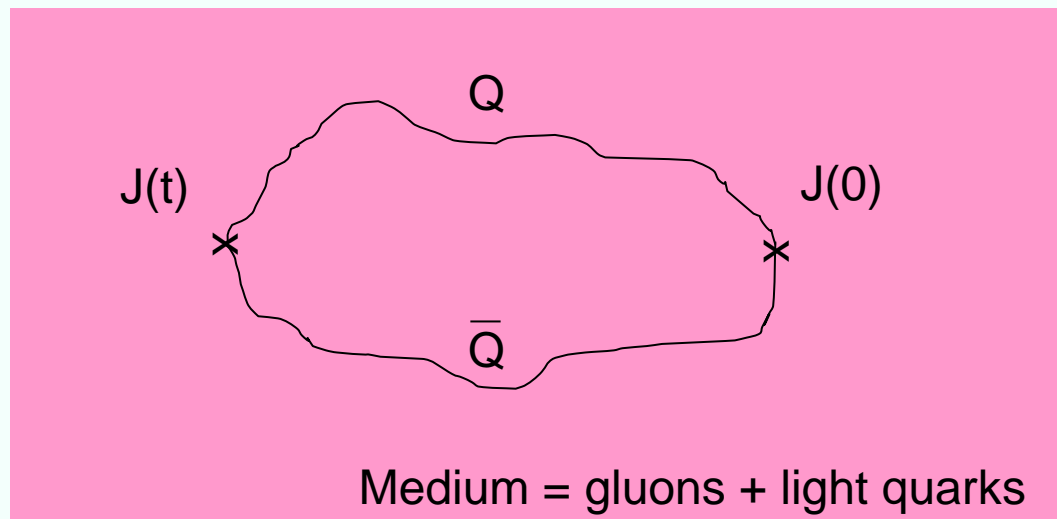
Emerick, Zhao, Rapp, EPJ A48 (2012) 72  
 Rapp, (Parallel 1D)



Young & Dusling, arXiv:1001.0935 [nucl-th]

Borghini & Gombeaud, EPJ C72 (2012) 2000; Dutta (Poster 47)

Akamatsu & Rothkopf, Phys. Rev. D85 (2012) 105011; Akamatsu (Poster 599)



Stochastic Schroedinger equation

$$\Psi(r, t) = \mathcal{T} \exp \left[ -i \int_0^t dt \left( \frac{-\nabla^2}{M_Q} + \text{Re}V(r) + \Theta(r, t) \right) \right] \Psi(r, 0)$$

$$\langle\langle \Theta(r, t) \rangle\rangle = 0, \quad \langle\langle \Theta(r, t) \Theta(r', t') \rangle\rangle = 2\Gamma(r, r') \frac{\delta_{tt'}}{\Delta t}$$

## Summary

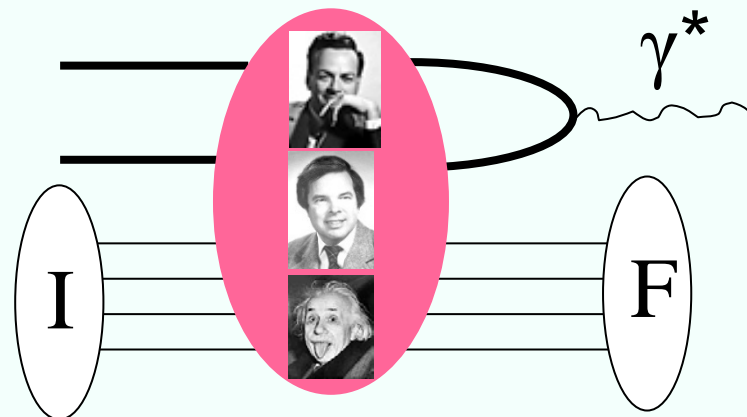
1. Heavy  $QQ\bar{b}$  : clean both experimentally & theoretically

## Summary

1. Heavy QQbar : clean both experimentally & theoretically
2. Heavy QQbar “free energy” is not the potential
3. Heavy QQbar “spectral function”
  - improvement necessary for nS states
  - not an observable at RHIC/LHC

## Summary

1. Heavy QQbar : clean both experimentally & theoretically
2. Heavy QQbar “free energy” is not the potential
3. Heavy QQbar “spectral function”
  - improvement necessary for nS states
  - not an direct observable at RHIC/LHC
4. Heavy QQbar “complex potential”
  - method established
  - quantitative results awaited
5. Heavy QQbar “phenomenology”
  - coming to a new era ?



## Parallel talks

1D

**PETRECKZY**, Heavy quark potential at non-zero temperature and quarkonium spectral Functions

**Rapp**, Comprehensive Analysis of in-Medium Quarkonia from SPS to LHC

2D

**Ding**, Momentum dependences of charmonium properties from lattice QCD

**Tuchin**, Gluon saturation effects on the color singlet J/Psi production in high energy dA and AA collisions

**Sharma**, High transverse momentum quarkonium production and dissociation in heavy ion collisions

6A

**CAO**, Heavy quark evolution and flow in hot and dense medium

## Posters

**396: GOSSIAUX**, Elastic scattering: The undersides of quarkonia propagation and collectivity in the QGP

**193: VAN HEES**, Heavy-quark diffusion at the LHC within a UrQMD-hydrodynamical hybrid model

**70: Gubler**, Hot quarkonium spectral functions from QCD sum rules and the maximum entropy method

**264: NAHRGANG**, Influence of a realistic medium description including fluctuations on heavy quark observables

**196: VOGEL**, Influence of the medium evolution on heavy quark observables

**51: UPHOFF**, Open heavy flavor and J/psi at RHIC and LHC within a transport model

**81: WOLSCHIN**, Upsilon suppression in PbPb collisions at LHC energies

**599: Akamatsu**, Quantum Description of Impurities - Heavy Quarks and Quarkonia

**464: Lang**, J/Psi suppression in high multiplicity proton-proton collisions at LHC Energies

**334: Vogt**, Improving the  $J/\psi$  Production Baseline in  $p+p$  and  $pA/d+Au$  Interactions at RHIC and the LHC

**194: Vogl**, Heavy quark energy loss in p+p collisions at the LHC

**47: Dutta**, HEAVY QUARKONIA IN MEDIUM AS OPEN QUANTUM DISSIPATIVE SYSTEM, A WAVE FUNCTION BASED APPROACH

**357: HE**, Nonperturbative Heavy-Flavor Diffusion and Hadronization in a Hydrodynamic Description of Heavy-Ion Collisions